Murdoch University - School of Engineering and Energy

Engineering Thesis

Development of the Photovoltaic Training Facility on the Engineering and Energy Building

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A report submitted to the School of Engineering and Information Technology, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering.

Abstract

Solar energy is an abundant resource, especially in Australia. While increasing numbers of households, businesses and utility companies are installing photovoltaics to combat climate change and ever increasing power bills, network operators are having to deal with the problems this can cause such as voltage rise and other power quality issues. Monitoring of PV systems is becoming increasingly more important in addressing such issues, as is localised environmental monitoring. Utilising different sensors to measure solar radiation, ambient temperature and wind speed, network operators are better able to predict and react to environmental changes which can affect the output of PV systems.

This report focuses on the installation of an environmental and PV inverter monitoring system for the Photovoltaic Training Facility on the Engineering and Energy Building at Murdoch University. This work follows on from that of Stuart Kempin who designed and managed the installation of the PV Training Facility and Mael Riou who designed much of the environmental monitoring system.

The environmental monitoring system consists of two anemometers, a wind vane, an ambient temperature sensor, two pyranometers (one mounted horizontally and one mounted on the plane of the PV array) and RTD temperature sensors for PV module temperature measurement. The communication interface for these sensors incorporates I/O modules from Avantech's ADAM 4000 series and communicates via RS485 with a computer running the LabView programming software for monitoring and logging purposes. Design work for the environmental monitoring system is now complete, including specifications and drawings for the mounting brackets.

For monitoring the PV inverters, serial communication is also utilised. Where required, each inverter is fitted with a serial communication card which is wired to the same computer used for environmental monitoring via an RS485 to USB adapter. Again, the LabView programming software is used to monitor the inverters. All physical aspects of the inverter monitoring system have been completed. This includes the selection and acquisition of a suitable computer interface along with enclosure design and construction to suit. Installation of serial communication cards in the inverters and wiring and connection of the inverters has also been completed.

Several smaller assignments were also undertaken over the course of the project such as the review of technical diagrams provided by the installer of the PV Training Facility and testing of the SMA Backup system to ensure correct functionality. Some background information on the functional earthing of PV arrays is given and discussed in relation to the PV Training Facility. Unfortunately,

final schematic diagrams of the system have not yet been obtained however sections of the actual system configuration including the functional earthing arrangement have been confirmed.

The eventual goal of the system is to provide a solid, safe and informative teaching platform which can be used in the future to educate students on the role such monitoring systems may have in real-world scenarios. It is also planned to utilise the system to compare PV technologies and inverter topologies and their reactions under different environmental conditions.

Acknowledgements

I would like to thanks Dr Martina Calais for her support and provision of knowledge throughout this project. Her efficiency, punctuality and willingness to provide time and information have been vital to the completion of this project.

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Special thanks must also go to:

- Mr Craig Carter for co-supervising my thesis. Craig's extensive knowledge and industry experience was highly valued throughout the course of the project.

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1.0 Introduction

Murdoch University has had a significant involvement with renewable energy for some time. It was one of the first universities in Australia to offer a bachelor's degree in Renewable Energy Engineering and currently has some of the best renewable energy research facilities in Australia (University, Murdoch 2013). As well as the 56kWp photovoltaic array installed on the library on the South street Campus, Murdoch University has recently invested in an 8kWp photovoltaic installation on the recently constructed Engineering and Energy Building.

The aim is to use this system as a teaching and learning aid as well as a research tool, allowing the observation of the environmental effects on the power output of different PV technologies and inverter topologies as well as monitoring the degradation and responsiveness to environmental change of each cell type. The inverters' response to change may also be monitored. The ability to perform detailed performance analyses and compare cell and inverter technologies is advantageous, as it will provide data which may be used for developing better PV systems as well as designing systems specifically depending on their location and needs.

This report will focus on the completion of the environmental monitoring system as well as the design and implementation of a monitoring system for the PV inverters. It will also report on the commissioning and testing of the PV systems and the review of technical diagrams. Over the course of the project, several smaller issues were met and will also be discussed in this report.

1.1 Review of Texts and Previous Work

This thesis project follows on from work by Stuart Kempin and Mael Riou.

The PV Training Facility was designed and its installation managed by Stuart Kempin for his final year engineering thesis (Kempin 2012) and was intended to be used as a teaching and learning aid.

The system consists of five solar PV systems comprising four different PV technologies, including polycrystalline, monocrystalline, CIGS (Copper Indium Gallium Selenide) thin film and amorphous. Five different inverter models were used from three different manufacturers, namely SMA, Fronius and Samil Power. A total of 8kW [DC] was installed.

As the installation is to be used as a teaching resource, monitoring equipment for both environmental conditions and AC and DC electrical parameters are required. Mael Riou took on the challenge of designing the environmental monitoring system in his thesis (Riou 2012). The system he designed consists of two anemometers, a wind vane, an ambient temperature sensor, two pyranometers (one mounted horizontally and the other mounted on the plane of the PV array) and RTD temperature sensors for PV module temperature measurement. The sensors are interfaced with a computer via I/O modules from Avantech's ADAM 4000 series and an RS485-PCI adapter. LabView programming software is used to monitor and log the incoming data.

Several standards were referred to over the course of the project including IEC61724: Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis; IEC61215: Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval, AS5033: Installation and Safety Requirements for Photovoltaic (PV) Arrays and AS4777: Grid Connection of Energy Systems via Inverters.

The technical manuals for each inverter and their respective serial interfaces were also utilised for information regarding connection and correct operation.

1.2 Background on the Photovoltaic Training Facility

Table 1 gives a description of the make/model of the equipment specified for installation in the PV Training Facility, the quantities of each and the configuration. Please see figure 2 for physical array configuration and figure 3 for the proposed system schematic and equipment location.

Table 1 - Specified system configuration

PV Modules					
	Monocrystalline	Polycrystalline	Amorphous	Thin Film (CIGS)	
Model	Sunpower E19	HHV	AmpleSun	Q.Cells	
	SPR-238E-WHT-D	HSDTDF24255P	ASF100	Q.Smart 90	
Array configuration					
Array number	1	2	3	4	5
Number of modules	9	8	20	6	16
Configuration	9S1P	8S1P	4S5P	3S2P	4S4P
Array power (W, nominal)	2142	2040	2000	540	1440
Inverter make/model	Fronius IG20	Samil Power SolarRiver 2300TL	SMA Sunny Boy SB2500HF	SMA Sunny Boy SB1100	SMA Sunny Boy SB1700
Inverter nominal power (AC, W)	1800	2000	2500	1000	1550

This facility is a valuable resource for teaching due to the multiple PV module technologies and inverter topologies. It allows the different types to be compared in an accurate way and with the inclusion of the monitoring system and enables the effects of weather on each system to be clearly demonstrated.

At the beginning of the project, the system was yet to be commissioned. Regular contact was made with the project manager, Julie Yewers, in the hope that the commissioning could be attended for documentation, however, due to a communication error this did not take place. The handover of the system by Vince Aitken (TPE services) was attended where several issues were identified. These and the subsequent resolutions will be discussed later in this report.

1.3 Cloud Fluctuation Impact on PV System Stability

As the production of energy in a PV system relies primarily on the availability of light from the sun, any rapid changes in this resource can have a substantial impact on the output of the system. In areas where there is a high level of PV penetration, this can cause problems with the stability of the wider electricity network. A case study performed in the Western Australian town of Carnarvon (Lewis 2012) states: “When the systems are highly clustered together (such as in the Carnarvon network), it is possible that large clouds can effectively reduce a large proportion of PV generation in a short period of time.” It goes on to say: “The combination of these effects is that passing cloud cover has the potential to cause large and rapid variation in PV system output...” (Lewis 2012).

The bulk of the energy produced in Carnarvon is supplied by gas and diesel generators and distributed on an isolated grid. PV penetration is estimated to peak at 13% of system load at midday. In a network such as this, a rapid fall in PV generation due to sudden cloud cover appears as a large load variation to the main generators which can, depending on generator ramps rates and spinning reserve, cause issues with system stability. This can mean issues with system frequency and generator overload as well as over and under-voltages throughout the network.

The PV Training Facility is designed to allow the monitoring of the effects of rapid changes in cloud cover on different system types. Once up and running, it will prove to be a useful resource for research into cases such as that in Carnarvon and will potentially allow for the design of systems which will provide better stability to smaller isolated grids.

1.4 Design Requirements

The system as a whole must be able to record high-resolution data from the environmental sensors as well as data from the PV inverters. The system must be user friendly as it will be used as a teaching aid with students. This also means it must be extremely safe, with no live parts easily accessible. The user interface should be informative and easy to use.

Other requirements include:

- Brackets for equipment which will be located outside must be corrosion and UV resistant and waterproof where required.
- All equipment must comply with the relevant standards.
- All equipment should be installed to meet the relevant standards.
- Provision for future improvement, development or expansion is desirable.

1.5 Project Timeline and Difficulties

Figure 1 shows a timeline of the project showing the major events involved with the project itself and the commissioning of the facility.

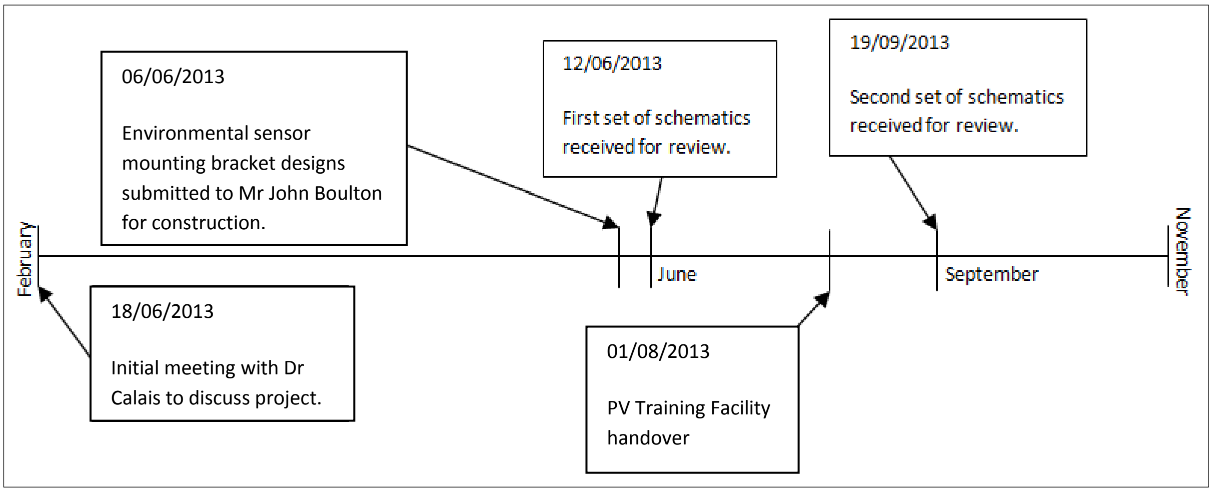


Figure 1 - Timeline of major project events

It may be seen from the timeline that there were significant hold-ups in the project such as the late commissioning and handover of the system, delays in the fabrication and installation of the mounting equipment for the environmental sensors and issues with the confirmation and finalisation of the schematic diagrams and system configuration. Unfortunately, these set-backs limited the amount of work which could be completed over the course of the project.

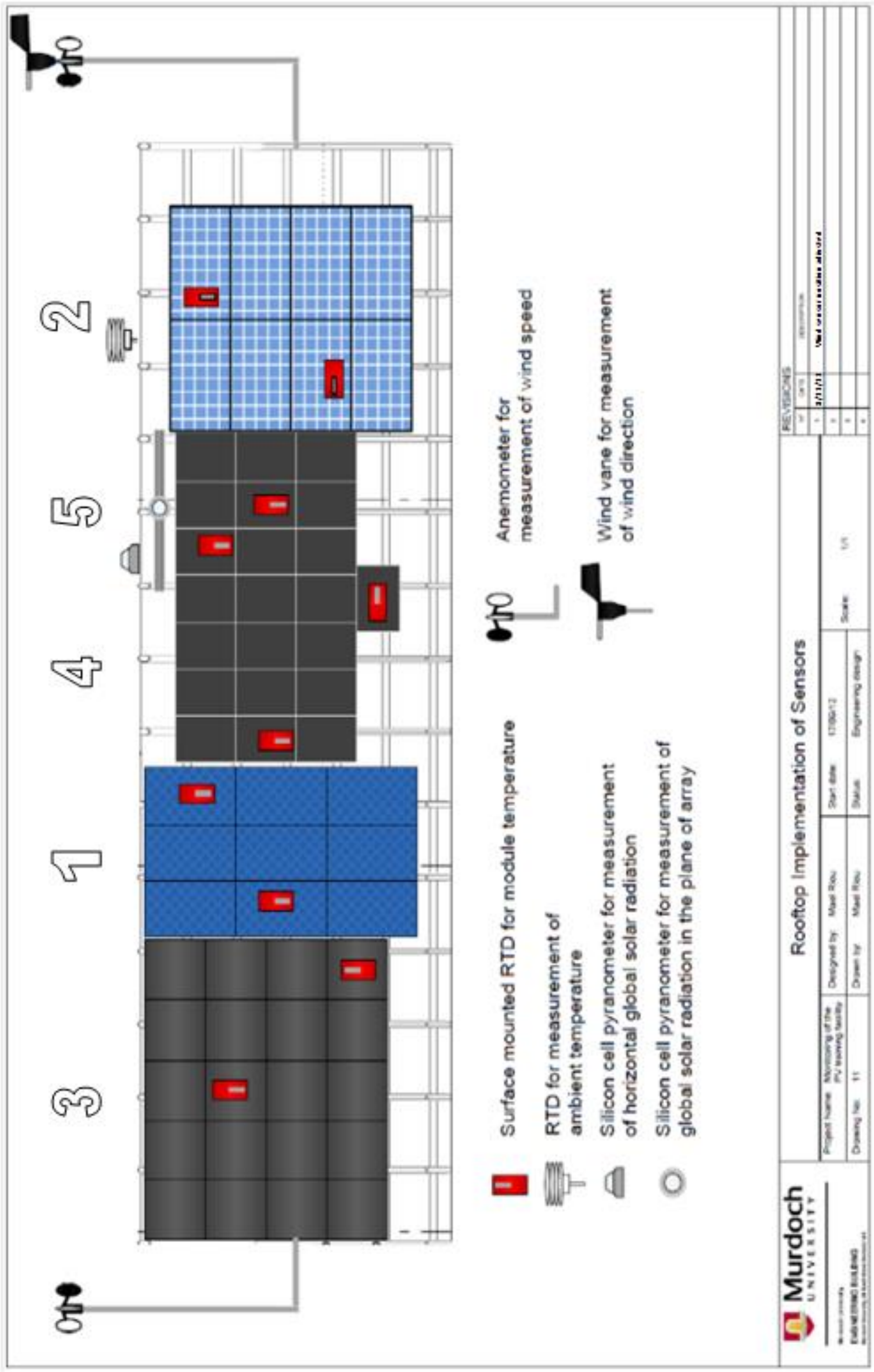


Figure 2 - PV array configuration and proposed environmental sensor positioning and locations (Riou 2012)

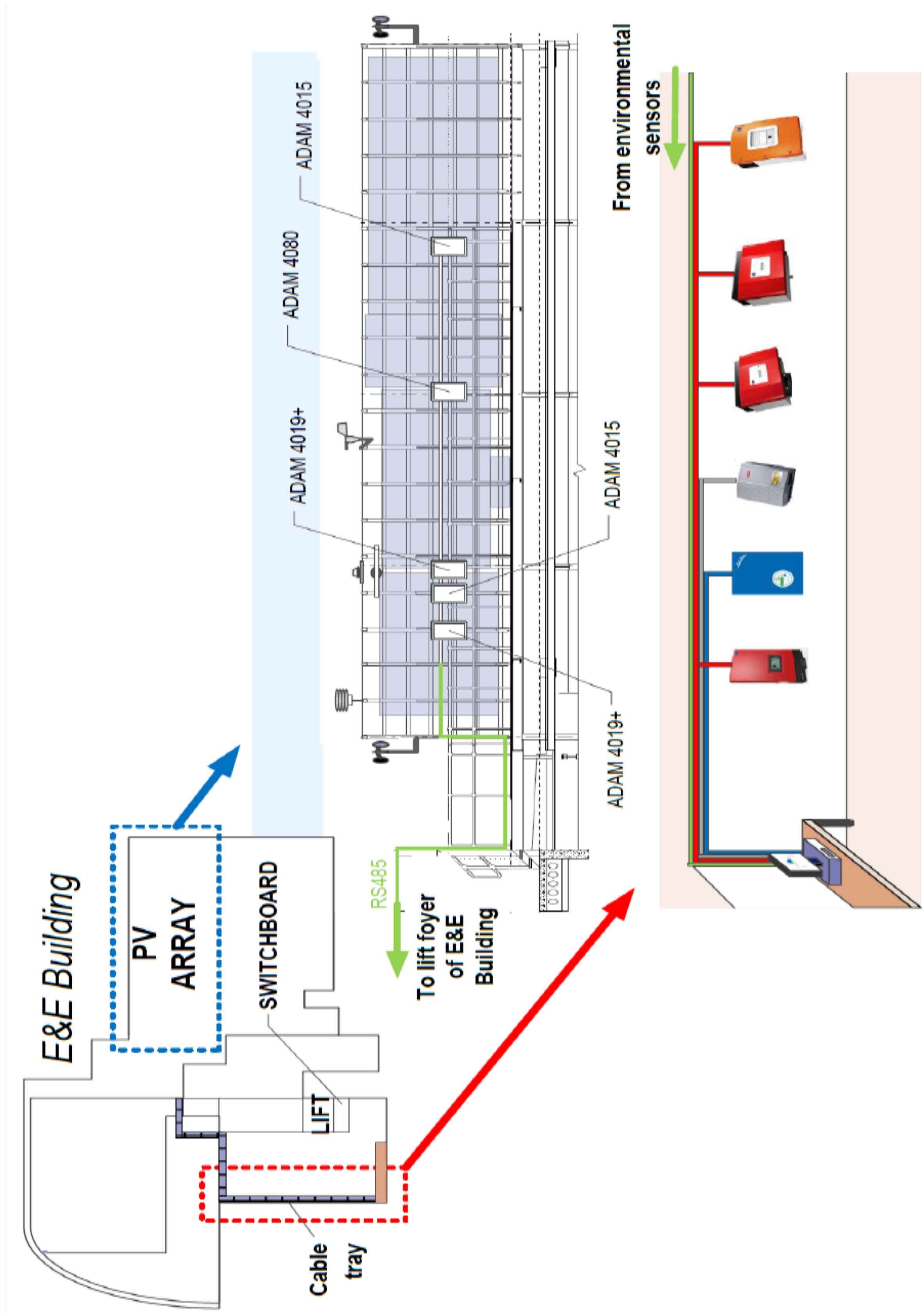


Figure 3 - Proposed system schematic and equipment location (Riou 2012)

2.0 Monitoring System

2.1 Initial System Status and Early Planning Decisions

At the beginning of the project, the PV systems were yet to be connected to the grid. Unfortunately, this meant any work on the inverter monitoring system was limited to design and component acquisition. Fortunately, there was some work to be done designing the mounts for the environmental sensors.

2.1.1 Equipment Status

Table 2 provides a summary of the equipment available at the beginning of the project, ordered by Mael Riou (Riou 2012). This list is for the environmental monitoring system only.

Table 2 - Equipment available upon commencement of project

Component	Type	Quantity
Sensors		
Surface mount RTD for module temperature measurement	TCS667PDZ40AC [RTD Pt100 Class B]	10
Ambient air temperature sensor (RTD)	RTD Pt100 Class A	1
Pyranometer	SP Lite 2 Silicon cell pyranometer [Kipp & Zonen]	2 [1 for each horizontal global radiation and global radiation in plane of array]
Anemometer	#40C anemometer [NRG Instruments 2008a]	2
Wind direction sensor	NRG #200P [NRG Systems 2008b]	1
Data Acquisition		
Advantech ADAM 4015	7CH RTD Remote I/O module	2
Advantech ADAM 4019+	8CH remote I/O module	2
Advantech ADAM 4080	2CH frequency counter/remote I/O module	1
4 Port PCI RS485 serial interface [NI]	-	1
RS485 communication cable [NI]	-	1

Table 3 shows a list of equipment which was required to complete the installation of the environmental monitoring system.

Table 3 - Equipment required to complete the installation of the environmental monitoring system

Component	Type	Quantity	Source
Mounting equipment			
Mounting boom for anemometer	Fabricated	2	Fabricated
Horizontal platform for pyranometer	Fabricated	1	
Horizontal platform for wind vane	Fabricated	1	
Horizontal platform for ambient temperature sensor	Fabricated	1	
Mounting rail for plane of array pyranometer	Fabricated	1	
Enclosure for remote I/O module	Weatherproof, secure	4	
Radiation shield for ambient temperature sensor			
Table for PC	-	1	Murdoch University
Cabling and associated needs			
Wiring for sensors	Weatherproof,twisted pair, shielded		
Protective insulation for RTD sensor cabling	Heat shrink/fibreglass		
RS485 cable	Twisted pair, shielded		
Cable ties	Stainless steel		
Conduit for power and communications cables	Plastic		

2.1.2 PV Inverter Interfacing

Table 4 is a summary of the equipment at hand at the beginning of the project. This list is for the inverter monitoring system only.

Table 4 - PV inverter interfacing equipment available at beginning of project

Component	Inverter	Quantity
SMA RS485 communication card	SB1100, SB1700, SBU5000	3
SMA RS485 quick module	SB2500HF	1
Fronius interface card easy	IG20	1

Most components are available with only an RS485 interface for the computer and the associated wiring, conduits and fixings required to complete the physical installation of the PV inverter monitoring system.

2.2 Environmental Monitoring Design

2.2.1 Mounting brackets

Mael Riou had completed a thorough design of the environmental monitoring system in his thesis (Riou 2012), however the location of the wind sensors, the design of the mounting brackets for these sensors and the pyranometers still needed to be done.

Several research facilities including the Fraunhofer Center for Sustainable Energy Systems (Fraunhofer USA 2012) and the Sandia National Laboratories PV Facilities (Sandia National Laboratories 2012) were examined for information on mounting the wind sensors. Two international standards were also consulted when determining the correct location for the wind sensors (IEC61724: Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis 1998) (Standards, International 2005). These standards specify that the wind sensors should be mounted 0.7m above the array and 1.2m to the East or West of the array. As two anemometers are to be utilised in this installation, one shall be installed to both the East and West, with the wind vane to be installed on the West side.

The pyranometers shall be installed centrally on the array, both horizontally and on the plane of the array. This allows the measurement of solar radiation on a horizontal surface as well as solar radiation on the plane of the array. The horizontal data is useful in creating a database which may be referenced when designing PV systems in the future while the latter measurement, along with cell temperature values, may be used to calculate the efficiency of the array.

After a discussion with John Boulton, it was decided that drawings and a description of the exact location and configuration of the sensors would be provided to him upon which time he would construct the mounts. Materials such as aluminium, galvanised steel and stainless steel will be utilised for their corrosion resistance. The diagrams and descriptions provided to him can be found in the appendix.

At the time of writing, no further progress has been made on the installation of the environmental monitoring equipment. As there is no further design work to be done, completion of this part of the project is easily achievable in the future.

2.3 PV Inverter Monitoring

2.3.1 RS485 Interface Selection

Research was done on possible options for interfacing the RS485 serial connection from the inverters with the computer that was to be used for monitoring and data acquisition. These options are given in table 5.

Table 5 - Serial interface options

Option	Product	Description	Website	Cost
1	USB-COM485-PLUS4	4 RS485 connections, USB interface	http://www.ftdichip.com/Products/Modules/USBRSxxx.htm **Buy:** http://australia.rs-online.com/web/p/products/6877758/?cm_mmc=AU-PPC-0411-_-google-_-3_EEM_MPN_Jun2012-_-usb-com485-plus4_Phrase	AUD $73 (free shipping)
2	RS485 HUB 7-WAY SPLITTER	RS485 7 way hub	http://www.daveonlinestore.com.au/rs485-hub-7-way-splitter-p-505.html	AUD $299 +shipping
3	StarTech.com 4-port RS-422/RS-485 Serial PCI Adapter Card	4 Port RS485 PCI card	http://www.overstock.com/Electronics/StarTech.com-4-port-RS-422-RS-485-Serial-PCI-Adapter-Card/4598130/product.html?cid=207675	AUD $251.90 +shipping
4	Shentek 4 port High Speed Serial RS 422/485 RS422/485 RS485 RS 485 PCI Card WIN8	4 Port RS485 PCI card	http://www.ebay.com.au/itm/271144445606?hlp=false#ht_4061wt_1397	~AUD$91 (free shipping)

After speaking with Mr Will Sterling about these options, it was decided that a USB interface would be the most appropriate for several reasons. Firstly, USB ports are common and will be a technology that will remain present in computers in the future, unlike PCI ports which are being phased out. Additionally, a USB interface makes changing computers easy should the need arise.

Option 1 was selected as it is a USB device, has 4 ports which allows for simultaneous use of the monitoring system and a power analyser as well allowing for future expansion. It was also well priced.

2.3.2 Computer Setup and Security

A desk is required on the top floor of the Engineering and Energy building to mount the computer which will be used for monitoring the PV inverters and environmental sensors. This computer was set aside by Mael Riou for his thesis (Riou 2012) and is already fitted with a PCI RS485 interface for the environmental sensor monitoring.

As this room is publicly accessible, some form of security is required to prevent tampering with the equipment and to ensure the area is safe. A power socket and Ethernet connection is also required in the area where the computer will be located. John Boulton was consulted and set up a temporary desk and extension lead so that progress on the project could be made. An Ethernet cable was also installed so the computer had access to the University's network and the internet. For configuration of the PV Training Facility room, please see figure 4.

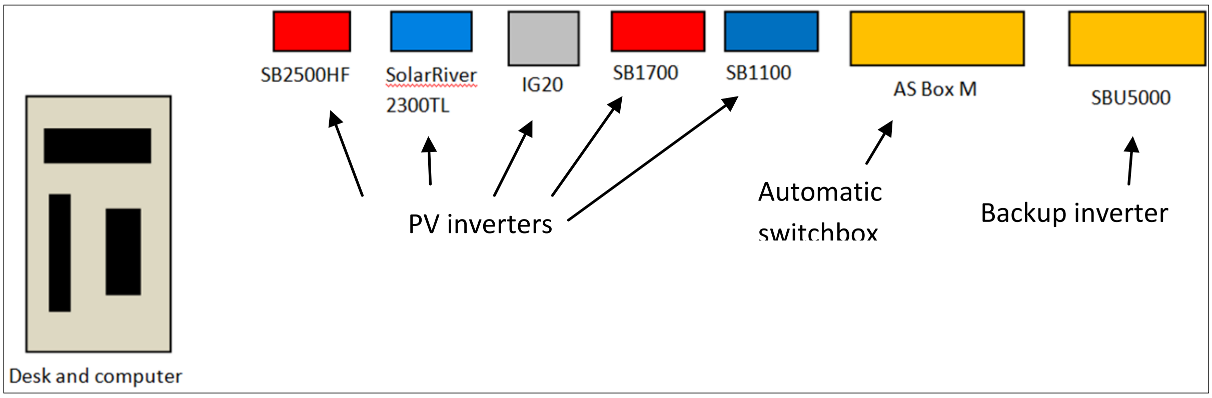


Figure 4 - PV Training Facility room configuration

2.3.3 Wiring Configuration

In order to communicate with the inverters and retrieve information from their sensors, a means of communication must be established. As serial expansion cards were purchased by Mael Riou for his thesis [2012], this method has been used. Figure 5 illustrates how each inverter will be interfaced with the data logging computer.

Each SMA inverter had an RS485 serial card installed by Will Sterling and Lafeta Laava. The SB2500HF received an RS485 quick module while each of the other SMA inverters was fitted with an RS485 communication card. As the SMA inverters utilise the same communication protocol, they were able to be daisy-chained (wired in parallel) and connected to only one port on the USB-RS485 interface.

The Samil Power inverter has an inbuilt RS485 interface and so this simply needed a cable installed and connected to the interface.

When the serial card was ordered for the Fronius inverter, it was thought to be an RS485 module however upon installation it was discovered that it was actually an RS232 card. On recommendation by Will Stirling, this inverter was wired to the computer's standard serial port.

All wiring is terminated with a DB-9 plug on the computer side.

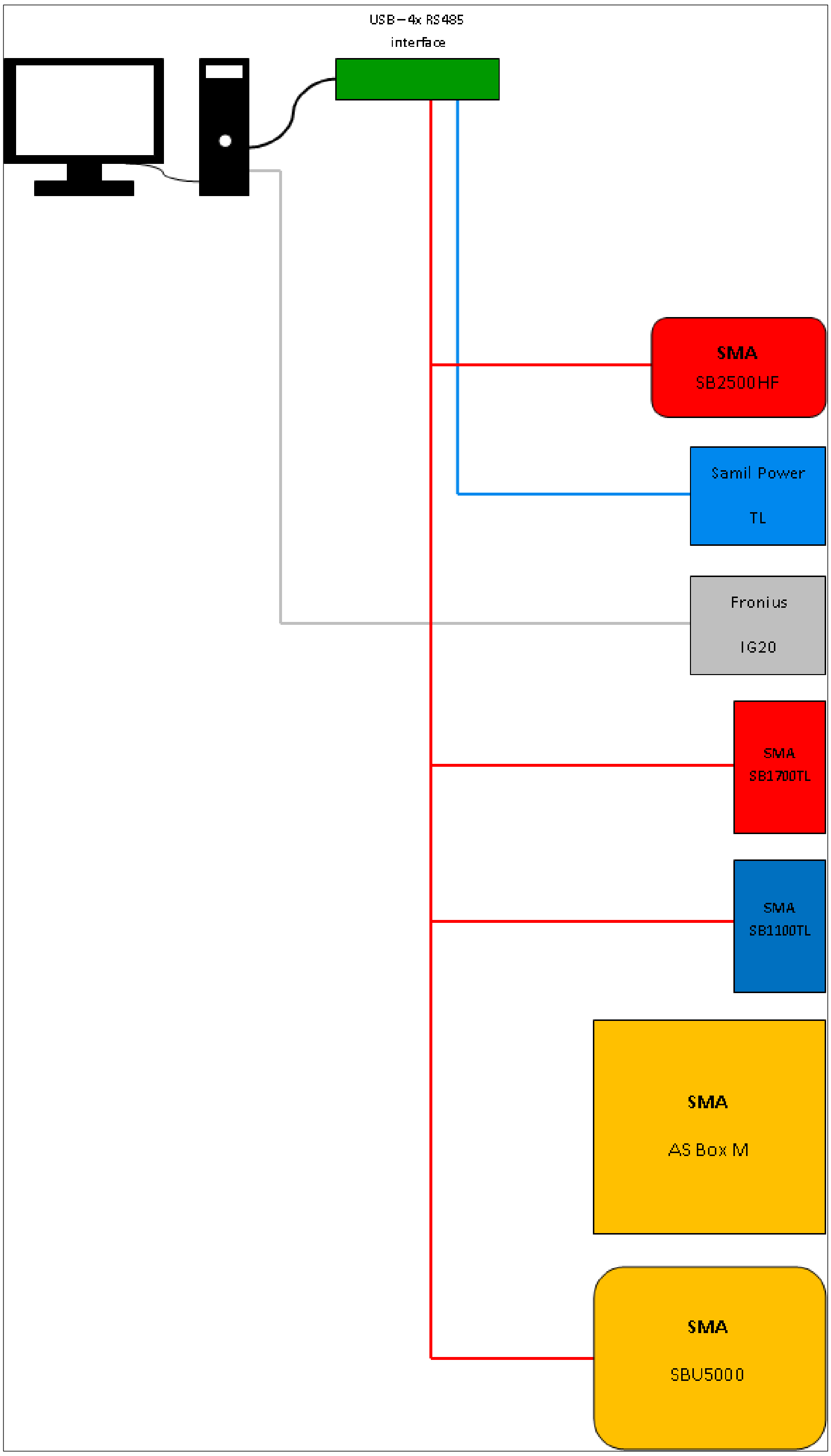


Figure 5 - PV inverter interfacing layout

2.3.4 SMA Daisy Chaining Wiring Diagram

Installation of the SMA Quick module to the 2500HF inverter simply involved clipping the unit into the bottom of the inverter. The RS485 communication cards for the other three inverters required the front panel of the inverter to be removed and the module to be installed on two sets of header pins on the circuit board inside the inverter [see figures 8, 9, 10 and 11]. Once the units were installed, shielded, twisted pair cable was run for all SMA inverters but the SBU5000 which required CAT6 cable. The cables were wired to the inverters as per figures 6 and 7 below.

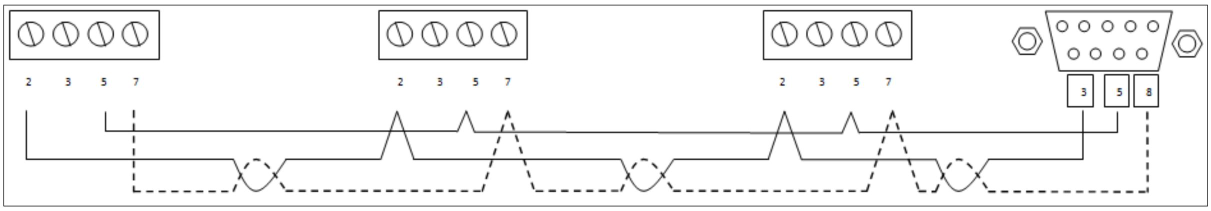
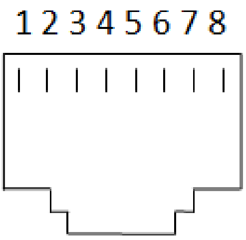


Figure 6 - SMA daisy chaining wiring schematic



Pin	2	3	6
Function	GND	Data+	Data-

Figure 7 – SMA SBU5000 RS485 pin configuration

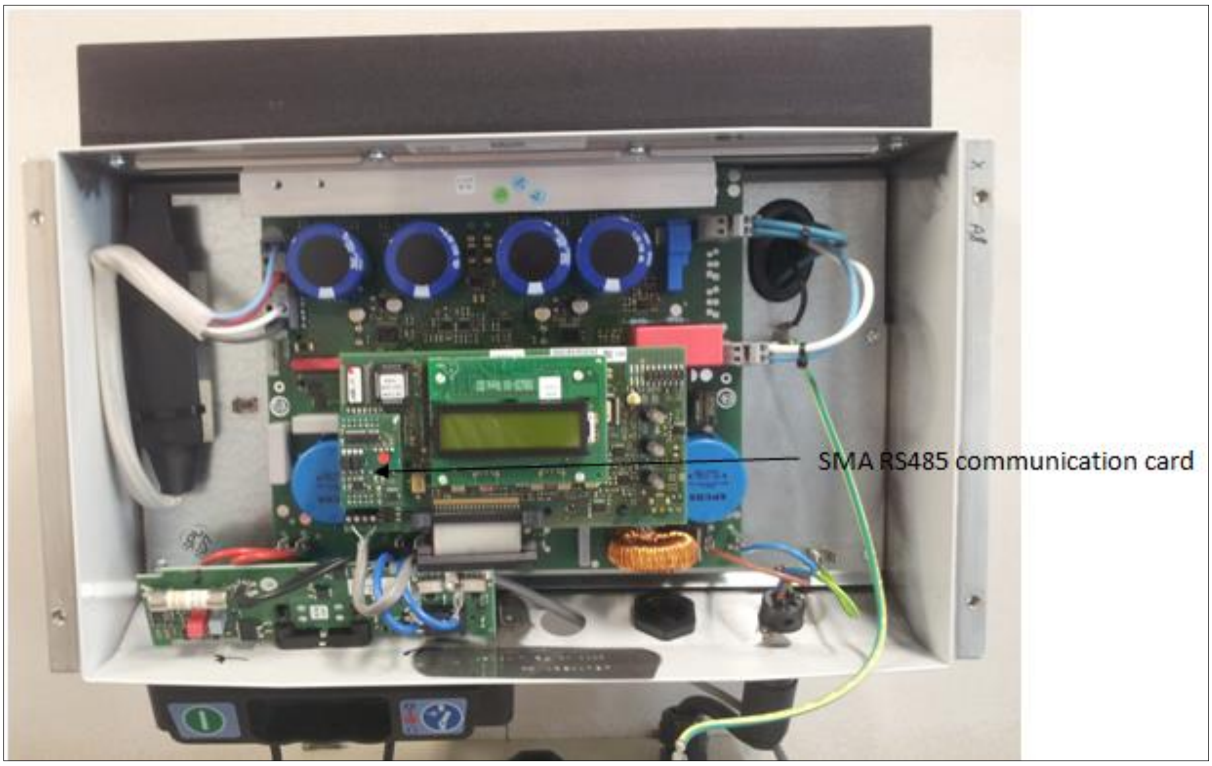


Figure 8 - SMA SB1100 with RS485 communication card installed

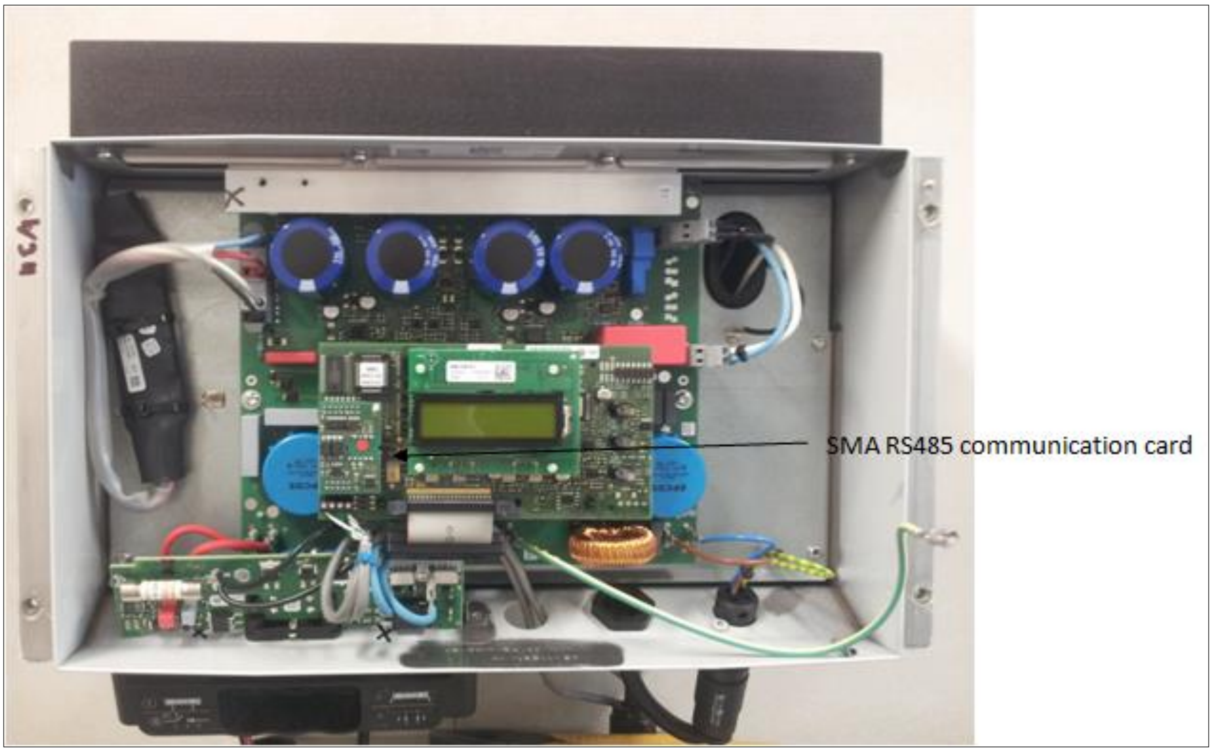


Figure 9 - SMA SB1700 with RS485 communication card installed

Figure 10 - SMA SBU5000 with RS485 communication card installed

Figure 11 - Close-up of RS485 communication card installed in SMA SB1700

2.3.5 Samil Power SolarRiver Wiring

The SolarRiver inverter has inbuilt both RS232 and RS485 serial interfaces. When wiring the RS485 interface, an RJ11 plug is used. This plug is of the type typically used to connect a telephone to a wall socket in Australia.

A grommet must be removed from the bottom of the inverter and the cable passed through it before a plug is crimped onto the wires. The plug can then be plugged in to the inverter and the grommet replaced.

The pin configuration of the RS485 socket is shown in table 6.

Table 6 - Samil Power RJ11 pin configuration

Pin	1	2	3	4
Function	Tx+	Tx-	Rx+	Rx-

2.3.6 Fronius IG20 Interface and Wiring

The Fronius IG20 inverter requires a small front fascia to be removed when installing the 'Interface Card Easy' serial communication card. The card then slots into a port on the circuit board, providing a DB-9 socket on the bottom of the inverter. The cable required is simply a DB-9 to DB-9 cable and is plugged into the standard serial port on the back of the computer.

2.3.7 Monitoring Software

There are many options when it comes to software which can be used to read and write data from and to a serial port. The requirements for this project are reliability, ease of use, flexibility, familiarity and the ability to modify or update the program as required. These stem from the eventual use of the PV Training Facility as a teaching and learning resource. Listed in table 7 are some of the options considered.

Table 7 - Monitoring software options

Interface	Pros	Cons
Labview	• Accepted industry tool • Flexible	• Can be difficult to use, especially for a beginner
Microsoft Excel	• Powerful data analysis tool • Flexible • Easy to use	• Possible manual operation
Matlab	• Powerful • Flexible	• Possible manual operation • May add unnecessary complication
123Solar (www.123solar.org)	• Already up and running • Nice user interface	• Lack of flexibility • Requires a domain name
Custom web interface	• Flexible	• Could be time consuming
Hyper terminal (paid) or Realterm (free and sounds better)	• Communicates well with RS485 devices • Can be controlled using Excel and all the data can then be manipulated in Excel	• Some coding requirements
Windmill 7	• RS485 data logging in real time • Can log in real time to Excel	• Some coding requirements

After consultation with Martina Calais on the matter, it was decided that LabView would be used for several reasons. Firstly, it would tie in well with the environmental monitoring system as LabView is used for monitoring the sensors used in that setup. LabView is also used in many of the University's engineering units, therefore there is a relatively large knowledge base on campus. It is also a powerful and flexible package and is used for many industrial processes (Instruments, National n.d.) which rely on its robust nature.

2.4 Serial Communication

2.4.1 Background on Serial Communication

Serial communication is a common communication protocol and comes standard on most computers in one form or another.

The concept behind serial communication is very simple, with the port sending and receiving bytes of data one bit at a time. While slower than parallel communication, which can send whole bytes at once, it is simpler and may be used over greater distances of up to 1200 meters as opposed to the maximum of 20 metres (with 2 metres at most between devices) that parallel communication is restricted to (Instruments, National 2013).

Three conductors, namely ground, transmit and receive, are used to send predominantly ASCII (American Standard Code for Information Interchange) data. Due to the asynchronous nature of serial communication, a port may transmit data on one line while it receives data on another (Instruments, National 2013).

Below are the most important characteristics of serial communication.

- **Baud rate:** a speed measurement which indicated the number of bit transfers per second. For example, 1200 baud is 1200 bits per second. The higher the baud rate, the lower the possible distance between devices (Instruments, National 2013).
- **Data bits:** a measurement of the actual number of data bits in a transmission. The most common values are 5, 7 and 8 bits. Here, the term 'packet' is used to refer to a single byte transfer (Instruments, National 2013).
- **Stop bits:** these are used to indicate the end of communication for a single packet. Standard values are 1, 1.5 and 2 bits (Instruments, National 2013). The purpose of stop bits is twofold; signalling both the end of transmission and also allowing for some error in the clock speed between the communicating devices. The more stops bits used in communication, the greater the acceptable tolerance between clock speeds but the slower the data transfer rate (Instruments, National 2013).
- **Parity:** a basic method of error checking commonly utilised in serial communication. There are four types of parity, namely, even, odd, marked and spaced with the possibility of not using parity also available (Instruments, National 2013).

2.4.2 RS232

RS232 serial communication is used in the Fronius IG20 inverter and enabled by the installation of the Interface Card Easy. RS232 is found in most IBM compatible PC's (Instruments, National 2013). It can be used for communication between things like computer mice and keyboards or industrial instrumentation. This method of serial communication is limited to point to point communication from computer to device, with up to 15 metres between the two (Instruments, National 2013).

2.4.3 RS485

RS485 is used in the communication between the SMA and Samil Power inverters and the computer. This serial communication method is an improvement over RS232 for several reasons. Firstly, multiple devices may be 'daisy-chained' (as is done with the SMA inverters) and connected to a single serial port. It also has greater noise immunity and may be used for serial communication up to 1220 metres (Instruments, National 2013).

2.4.4 RS485 Interface Overview

The interface ordered is from FTDI chip and comes as a bare circuit board. It requires a USB A to mini USB B cable for power and data connection to the computer. It features 4 serial ports, each with its own TxD (red) and RxD (green) activity LED's. It also features a yellow power LED.

2.4.5 Enclosure Design

To protect the interface from the environment and tampering, an enclosure needed to be designed. Google SketchUp was utilised and a design was created (see figure 13). The enclosure design is made compact so as to allow for space efficient mounting if required. It also includes mounting tabs so it may be fixed to a surface if required. The screws which hold the top and bottom pieces of the enclosure together are located underneath the enclosure when it is mounted, increasing security to the interface inside. The design was optimised for 3D printing and was printed on a Solidoodle 2 3D printer using ABS plastic. The interface installed in its enclosure is shown in figure 12.

Figure 12 - RS485 to USB interface in 3D printed enclosure

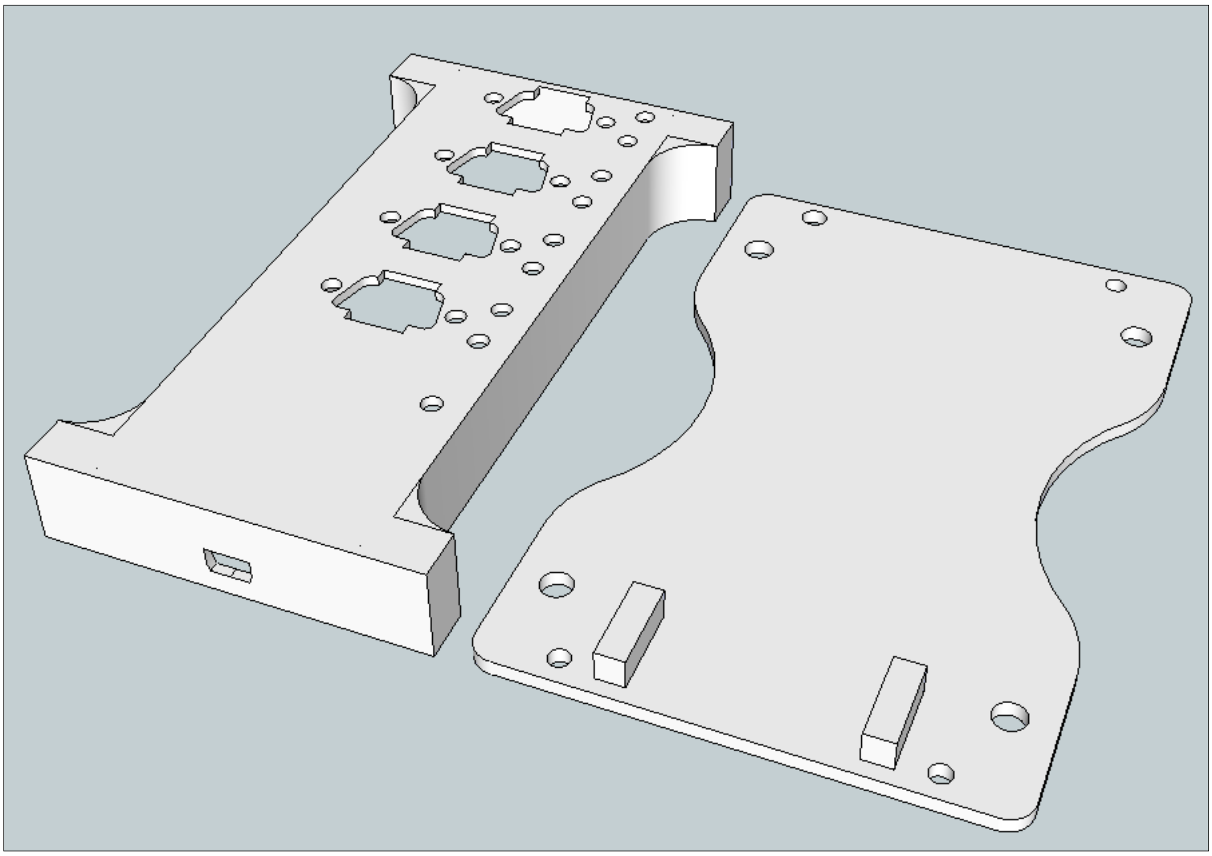


Figure 13 - Google SketchUp model of RS485 to USB enclosure

2.5 Monitoring System Conclusions

The physical design of the environmental monitoring system has been completed. Once the mounting brackets are fabricated and installed with the sensors, it is just a matter of running the cabling and making the necessary connections to complete the environmental monitoring system. Once up and running, the system will allow for accurate, high-resolution data collection with the ability to expand, alter or upgrade the system in the future. Although the surrounding buildings and trees limit the use of wind data as a meteorological tool, the data which will be recorded in the context of monitoring for the effects on the PV systems will be highly valuable, especially considering the utilisation of two anemometers.

All of the components for the PV inverter monitoring system are at hand. All that is required to complete the setup is a LabView program written to query the inverters and record their reply while displaying the data in a useful manner. Although the data which will be recorded this way will be of value, it is not a particularly accurate way to measure the parameters of a PV system as it relies on the internal sensors of the PV inverters. To record highly accurate values, the integration of a power analyser is necessary. This is discussed in section 5.4.

3.0 PV Training Facility Review

3.1 Functional Earthing

3.1.1 Functional Earthing Background and Effects

Some PV installations require either the positive or negative DC terminal to be connected to earth, either directly or through a resistor. This is called functional earthing, differing from protective earthing which involves non-energised conductive parts on equipment being connected to ground to prevent a wiring fault, potentially causing injury or death. Functional earthing is usually necessary on an array which uses thin-film or back-contacted PV modules. There are several reasons this may be necessary.

- **TCO (Transparent Conductive Oxide) corrosion:** TCO is used in some types of PV module and is the electrically conductive layer on top of the semiconductor material (SMA 2010). TCO corrosion occurs when a module has a negative potential with respect to ground (SMA 2010). Damage to the TCO layer is non-repairable and results in loss of power from the module (SMA 2010). The effects of TCO corrosion can become apparent after several months of use but may not appear until years after installation. Visual damage is usually in the form of 'bar-graph corrosion' (Fraunhofer Institute 2009). This type of damage appears on the front of the modules and looks like bars of different lengths.

- **Polarisation effect:** Solar cells which utilise 'back-contact' technology are susceptible to the polarisation effect when a positive potential with respect to ground exists (SMA 2010). These cells have an electric field which is concentrated on the back of the cells. A static negative surface charge can build up on the anti-reflective coating of these cells. Polarisation is reversible, meaning that permanent damage does not occur (SMA 2010).

3.1.2 Functional Earthing in the PV Training Facility

The PV Training Facility utilises three module types spread over four arrays which require functional earthing. These include:

- Amplesun ASF100 amorphous modules
  - Require negative functional earth (Amplesun 2009). The Amplesun ASF100 amorphous modules utilise TCO technology and require negative functional earthing to prevent TCO corrosion.
- Sunpower E19 monocystalline modules
  - Require positive functional earthing as these modules utilise back contact technology.
- Q.Cells Q.Smart thin film (CIGS) modules
  - Require negative functional earthing (Q.Cells 2011). The Q.Cells CIGS modules utilise TCO technology and therefore require function earthing of the negative terminal via a 35 ohm resistor. This limits ground fault current to 30mA (Q.Cells 2011).

Although a final installation diagram was not available at the time of writing, some investigation was done into the earthing configuration of the inverters. Shown below in figures 14 and 15 are the SB1100 and SB1700 inverters with a negative earthing kit installed. This is the correct configuration for the Q.Cells modules which feed the inverters.

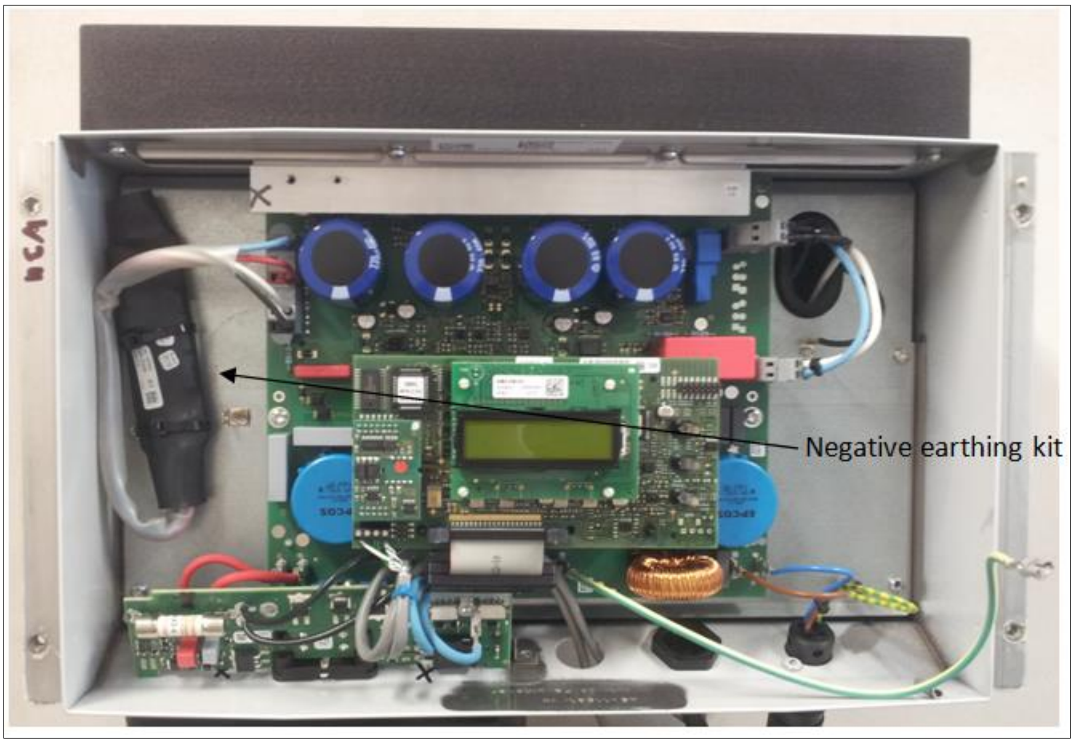


Figure 14 - SMA SB1700 with negative earthing kit installed

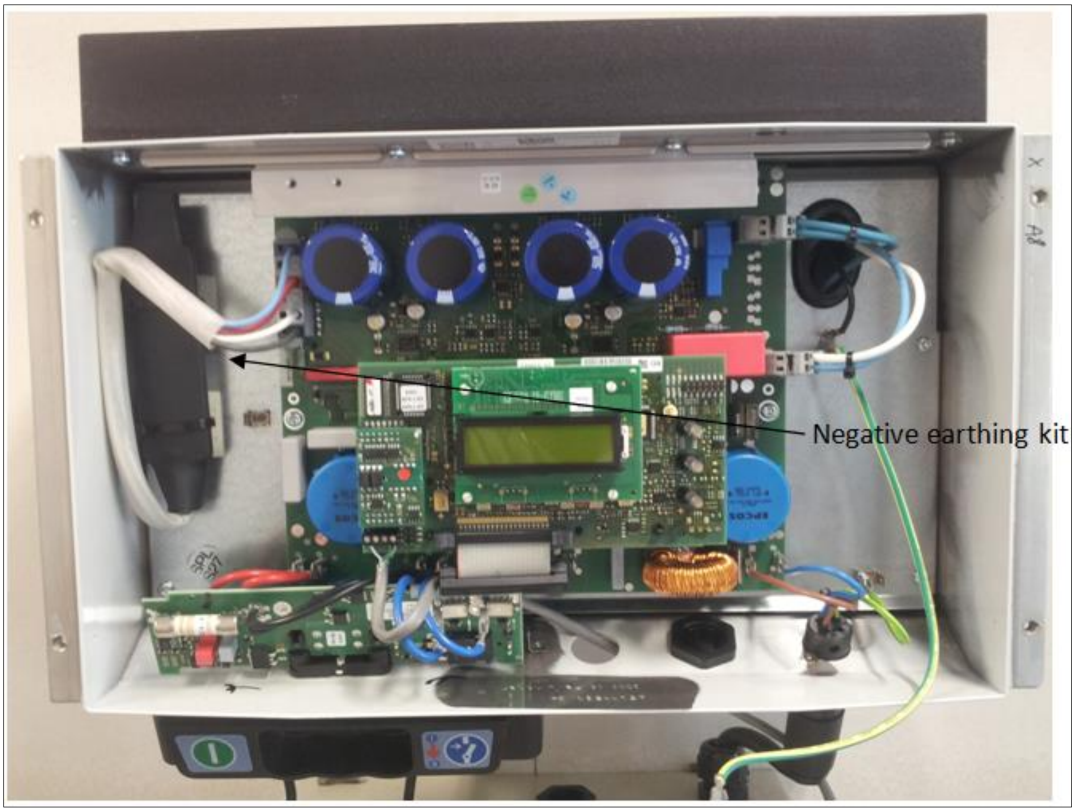


Figure 15 - SMA SB1100 with negative earthing kit installed

Due to the lack of finalised diagrams, it was unknown which PV array was connected to which inverter in the case of the SMA SB2500HF and the Fronius IG20. With the help of Dr Martina Calais and Mr Craig Carter, the SunPower array was partially shaded. This prompted a significant power drop on the IG20 inverter, confirming that the SunPower array was connected to this inverter. The test was repeated with the AmpleSun array to provide confirmation that this array was connected to the SMA inverter.

The SMA SB2500HF uses an external earthing kit in the form of a small cylinder which is plugged in to the bottom of the inverter. The cylinder has a '+' on one side and a '-' on the other. Whichever symbol faces the front of the inverter when it is installed determines whether the array has positive or negative functional earthing (SMA 2004). Upon investigation it was found that the array had been positively earthed. This is incorrect as the AmpleSun modules require negative earthing. The effects of this are not well documented as no information could be found on the subject.

The Fronius IG20 inverter utilises an external earthing method where the positive terminal of the array is simply connected to the protective earth by a short length of wire (SunPower n.d.). With assistance from Mr Lafeta Laava, the scutcheon plate in the solar supply switchboard for the Fronius inverter was removed. Once removed, the earthing link between array positive and protective earth is clearly visible and can be seen in figure 16.

Figure 16 - Fronius solar supply switchboard showing positive earthing link

While the SunPower modules do require positive functional earthing, it appears that the inverter's settings have not been changed, as required when functional earthing is installed (SunPower n.d.).

It is apparent that functional earthing was a stumbling point in this installation and may not be fully understood by the system's installers.

3.2 SMA SBU5000 testing

Figure 17 provides a simplified schematic of the SMA Backup system.

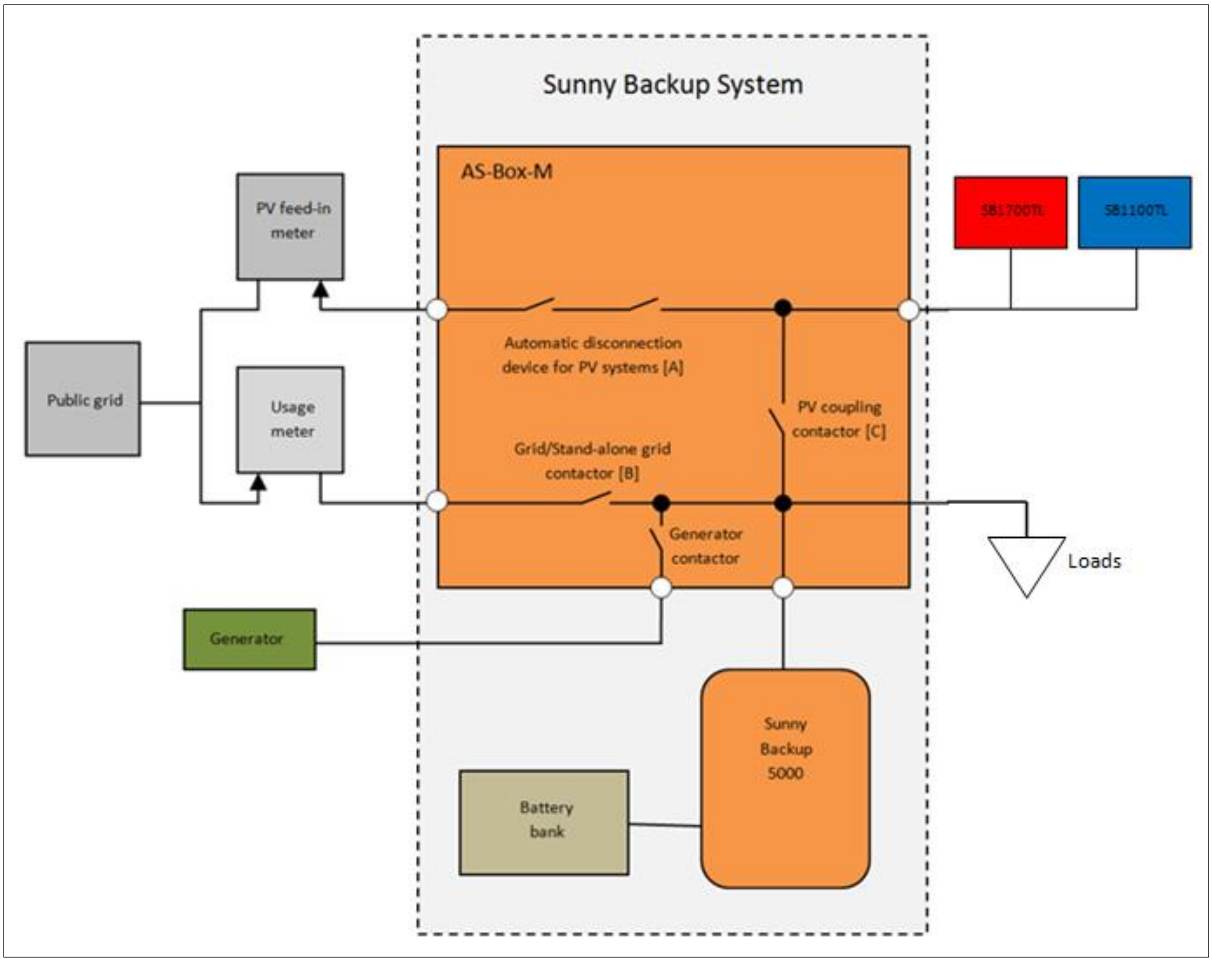


Figure 17 - Schematic diagram of SMA Sunny Backup system

3.2.1 System Operation Overview

After commissioning of the PV systems, tests were carried out on the Sunny Backup unit to ensure its correct operation as well as gain some insight to its workings. The tests were performed using a heating element/fan load and were done on an overcast day.

Figure 17 shows the configuration of the backup system. When operating correctly, the system should function as follows.

When connected to the grid, contactors A and B should be closed and contactor C should be open. When the grid fails the contactors at A and B should open immediately and, after the system has established that the grid is staying down (ie. not a brownout or momentary blackout), contactor C will close after 60 seconds. This allows the PV inverters to see the local AC voltage produced by the SBU5000 and reconnect their internal contactors, allowing the PV array and inverters to supply the load, with any extra power used to charge the batteries.

In the event that the batteries are fully charged and there is excess power being generated in stand-alone operation mode, the SBU5000 is designed to shift the output frequency slightly, causing the PV inverters to ramp down their output (SMA 2007). Unfortunately, the correct setup of the PV inverters is yet to be determined and they are currently utilising their standard over-frequency protection to trip their internal relay when the SBU5000 raises the frequency of the stand-alone grid. It is important to establish the inverters' current programming and rectify it, as required, to use the ramp-up/down functionality, as it will prevent premature wear of the inverters' relay contacts and allow for better charge management by the SBU5000.

Once the grid is restored, the system takes 60 seconds to react, delaying the reconnection of the Sunny Backup to ensure the grid has returned permanently. After this time, contactor C is opened and contactors A and B are closed. This action causes the PV inverters to drop out however they should reconnect after 60 seconds (Standards Australia AS4777 2005) and begin to supply the load and feed the grid with any additional power.

3.2.2 Test 1 – Operation Under Load in a Blackout and Restoration Situation (short term outage)

With the system connected to the grid, the load was turned on. The load drew some power from the grid as the PV inverters could not meet the demand. The grid was then switched off via the AC circuit breaker and the load was supplied by the batteries and the SBU5000 inverter. The switchover of contactors A and B was unnoticeable other than the temporary shutdown of the Sunny Boy inverters. The load was run until both inverters reconnected via their internal contactors 60 seconds after contactor C and began to supply the load. The grid was switched on and after one minute (Standards Australia AS4777 2005), the switchbox reconnected the grid to the system by opening contactor C and then closing contactors A and B. The Sunny Boy inverters disconnected and then reconnected via their internal switches after one minute (Standards Australia AS4777 2005). Operation was as expected and each stage of the test can be seen in figure 18.

Figure 18 - SMA Sunny Backup relay operation under testing

3.2.3 Test 2 - Operation Under Load in a Blackout and Restoration Situation (medium term outage)

With the system connected to the grid, the load was turned on. The load drew some power from the grid as the PV inverters could not meet the demand. The grid was then switched off via the AC circuit breaker and the load was supplied by the batteries and the SBU5000 inverter. The switchover of contactors A and B was unnoticeable other than the temporary shutdown of the Sunny Boy inverters. The load was run until the batteries are discharged to 98%. During this time, the SB1100's internal contactor remained disconnected due to a frequency disturbance (frequency over 51Hz) while the SB1700 cycled between connected and disconnected via its internal contactor. The SBU5000 showed the charge operation to be 'float' as the battery charge level remains above 70% (Standards Australia AS4777 2005). This operation is described in the SBU5000 manual, section 13.5. The grid was switched on and after one minute (Standards Australia AS4777 2005), the switchbox reconnected the grid to the system by operating contactors A, B and C. The Sunny Boy inverters disconnected and then reconnected via their internal switches after one minute (Standards Australia AS4777 2005). As the settings of the PV inverters have not been confirmed, it is not known why the inverters behave differently. Once the settings have been retrieved from the inverters, the reason for this operation can be determined and corrected, if required.

3.2.4 Test 3 - Operation Under Load in a Blackout and Restoration Situation (long term outage)

With the system connected to the grid, the load was turned on. The load drew some power from the grid as the PV inverters could not meet the demand. The grid was then switched off via the AC circuit breaker and the load was supplied by the batteries and the SBU5000 inverter. The switchover of contactors A and B was unnoticeable other than the temporary shutdown of the Sunny Boy inverters. The PV inverters were switched off via the DC circuit breaker in order to discharge the batteries at a faster rate. The load was run for approximately 1 hour until the batteries were discharged to 96%. The load was then switched off and the PV inverters were reconnected via the DC breaker. After one minute (Standards Australia AS4777 2005), the PV inverters' internal contactors reconnected and the inverters began to feed power into the system, charging the batteries. As the batteries were close to being full, neither inverter remained on for long before the SB1100 disconnected via its internal contactor and the SB1700 started to cycle as in test 2. The grid was switched on via the AC circuit breaker and after one minute (Standards Australia AS4777 2005), the switchbox reconnected the grid to the system by opening contactor C and closing contactors A and B. The Sunny Boy inverters disconnected and then reconnected their internal relays after one minute (Standards Australia AS4777 2005).

3.2.5 Test Results

While the complete disconnection of the Sunny Boy inverters does the job of reducing the feed in power during stand-alone grid operation, it is not ideal. The inverters can be set up to use a "Frequency Shift Power Control" system, as described in the SBU5000 manual, section 17.1 (SMA 2007). This allows the output power of the Sunny Boy inverters to be ramped down rather than utilising discreet on/off control. To activate this function, an installer code is needed and can be obtained from SMA.

Another concern with the system is the lack of battery temperature monitoring. The SBU5000 comes with provision for a temperature sensor, however it is not installed. Section 6.4.1 of the SBU5000 manual states, "A battery temperature sensor is provided with each Sunny Backup 5000." (SMA 2007) Section 6.4.1 also states, "The battery temperature sensor measures the temperature of the connected battery. This is necessary since the optimum charging voltage for a battery strongly depends on the temperature." (SMA 2007)

The charge current delivered to the batteries can be adjusted as described in section 14.4 of the SBU5000 manual (SMA 2007).

3.2.6 SBU5000 Charge Regime

The SBU5000 has a sophisticated charging regime. In this system, the charge current is limited by the lowest value of the maximum defined battery current, the nominal grid current or the maximum AC charging current of the SBU5000. The first phase (constant current phase) uses this limit and raises the voltage of the batteries as they are charged.

Once the batteries reach a predefined voltage the charging enters phase 2, the constant voltage phase or absorption phase. This sees the battery voltage maintained at a constant level, causing the battery current to continually decrease. The system will remain in this phase for a defined period of time. The system chooses one of three charging processes during this phase, as described below.

- Boost charge: enables the battery to be charged to approximately 85% to 90% using a high charge voltage for a short period of time.
- Full charge: After a discharge of more than 30%, the system will initiate a full charge if it has been longer than 14 days since the last grid failure. This process aims to charge the batteries to a level of at least 95%.
- Equalisation charge: After a discharge of more than 30%, the system will initiate an equalisation charge if it has been over 180 days since the last grid failure. This process aims to charge the batteries to a level of at least 95% to 100%. During this process, the system performs controlled over-charging of the battery bank to ensure any weaker cells are fully charged. It also acts as battery maintenance and extends the life of the battery bank.

During phase 2 of the charging process, the remaining charge time and the current process are displayed on the inverter's LCD.

Phase 3 is float charge which again uses constant voltage charging but at a reduced charging voltage. The purpose of this phase is to keep the batteries fully charged without overcharging which would cause premature aging of the cells. The system will remain in this phase until either more than 30% of the battery banks' capacity has been used or the charge state is below 70%.

The charging process is dependent on battery temperature. For temperatures below 20°C, the charging voltage is increased slightly and for temperatures over 20°C it is reduced slightly. This is to prevent overcharging and increase charging reliability. The charging voltage is reduced by 4mV/°C/cell for the current battery bank type (SMA 2007).

3.3 Review of PV Training Facility Schematics

One of the major challenges faced over the course of this project was the incomplete status of the equipment. Julie Yewers, the project manager for the original installation, was kind enough to provide updates of the progress along the way.

One of the issues that required resolving was the lack of accurate and detailed schematics for the facility. At several stages, drawings were provided however they proved very inadequate and somewhat inaccurate. As such, I was asked by Martina Calais to review the diagrams to aid in the resolution of this part of the system.

Some of the issues discovered in the schematic diagrams include:

- Lack of string wiring detail for PV arrays
- Battery bank configuration missing
- No ratings given for surge protectors, cables, circuit breakers and several other pieces of equipment
- String fuses missing from diagram (AmpleSun array)
- Test loops and terminals missing from diagram
- Incorrect configuration shown for SMA Backup system
- No functional earthing shown

Unfortunately, many other omissions and errors were discovered in each set of drawings received. Overall, this represents an incomplete service especially when coupled with the other issues related to the installation of the facility.

3.4 PV Training Facility Conclusions

Despite the many setbacks and difficulties associated with getting the PV Training Facility commissioning finalised, valuable progress has been made. A lot has been learned when it comes to functional earthing; knowledge which will hopefully be passed on to the system installers for their future use. While final drawings and confirmation of correct installation have not yet been established, it was interesting to have been part of the operation and see how businesses operate. Also providing an insight was the review of schematics for the PV Training Facility. More a lesson of what to avoid doing, the review of these diagrams was useful in determining possible issues with the system and errors in its installation.

As part of the verification of correct installation, testing was performed on the SMA Backup system, incorporating SMA SB1100 and SB1700 PV inverters, an SMA AS-BOX-M and an SMA SBU5000 backup inverter to ensure correct operation. While the settings of the two PV inverters related to their ramp-down functions are yet to be determined and adjusted where necessary, extensive documentation on the operation of the system as a whole has been created and will no doubt be valuable in the future when using the facility for teaching and research.

4.0 Conclusion

The PV Training Facility on the Engineering and Energy Building at Murdoch University is on its way to becoming a very valuable resource for teaching, learning and research into the effects of environmental factors on different PV cell technologies and inverter topologies.

This project aimed to provide a monitoring setup for the facility, following on from work by Stuart Kempin (Kempin 2012) and Mael Riou (Riou 2012). The design for the environmental monitoring system was completed by the realisation of the necessary mounting brackets and equipment required for the environmental sensors through the use of the CAD software Google SketchUp. Whilst delays in the fabrication of the brackets limited progress, minimal input is needed to finalise this aspect of the project.

The PV inverter monitoring system was also delayed by several factors, however the physical construct of the system is all but complete. The installation of the serial communication cards in the inverters and subsequent wiring was made simple with help from Mr Will Sterling and Mr Lafeta Laava. The USB-RS485 serial interface card which was purchased for communication of the inverters with the computer is housed in a 3D printed case, designed to protect it from physical damage and tampering. It was chosen for its flexibility, low cost and provision of spare serial ports for communication with a power analyser in the future. With the creation of LabView scripts which read, interpret, display and log the data from the inverters, the PV inverter monitoring system will be complete.

The requirement of several of the PV modules installed at the PV Training Facility to have functional earthing is something which caused some confusion.

5.0 Future Work

Due to time constraints and several other factors, work was not completed on the PV Training Facility. This does mean, however, that there is scope for further work by other students.

5.1 Work to be done on the environmental monitoring system

Completion of the environmental monitoring system requires the fabrication and installation of the mounting brackets by John Boulton. Once the brackets are installed, the sensors can then be mounted. It also requires wiring to be installed, including conduits and cable trays, where necessary. Once the wiring is in place, it is simply a matter of installing the ADAM modules along with the other serial communication equipment and ensuring the LabView scripts written by Mael Riou (Riou 2012) are functioning as intended.

5.2 Work to be done on the PV inverter monitoring system

To complete the inverter monitoring system, a LabView script must be written which can communicate with the PV inverters. As suggested by Graeme Cole [Associate Professor], several procedures should be used to separate the process. For example, one script could query the inverters, another could decipher the data received, another could plot to a GUI and yet another could record the useable data to a server. The installation of cable trays to run the serial cable safely and neatly also needs to be arranged.

5.3 Work to be done in the PV Training Facility

To create an environment more conducive to teaching and learning, a more permanent arrangement must be organised for the monitoring computer. Ideally, a cabinet should be installed which would house the computer and serial interface. This would aid in the prevention of vandalism or tampering while also ensuring the equipment is safe to use.

It is also necessary to finalise the installation. This includes obtaining accurate copies of the installation schematic and rectifying the issues discovered with the functional earthing.

As part of the verification of installation, the settings of both the SB1100 and SB1700 should be retrieved via the use of the serial communication setup. This is necessary to ensure that the inverters are correctly configured for use in the Sunny Backup system. Specifically, the ramp-up/ramp-down functionality of the inverters must be checked and adjusted, as required, as it is currently believed that the inverters are simply utilising their over-frequency protection to disconnect when the SBU5000 raises the frequency in the attempt to ramp-down power generation.

Another area where more testing would prove helpful is the Sunny Backup system. Deeper discharge of the battery bank using a larger load would allow for more tests to be conducted on the systems' response under different conditions. It would also provide an accurate measurement of the real-world capacity of the battery bank.

5.4 Power Analyser

The integration of a power analyser into the PV Training Facility would be beneficial, as it would allow the capture and recording of high-resolution data from the inverters. This is valuable when analysing the effects of sudden cloud cover and other weather and location related interference.

In order to provide this functionality to the PV Training Facility, a means of connecting to the inverters to read voltage and current is required. This could be achieved in several different ways, however it is important to bear in mind that the facility will be used for teaching and learning and therefore users must not be exposed to voltages exceeding 50VAC or 120VDC, defined as extra-low voltage by Australian Standards and suitable for work on and modification to by a "competent person" (Standards Australia AS4509.1 2009). The use of current and voltage transformers is recommended as these devices are commercially available and are very accurate.

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Appendix

Documents provided to John Boulton specifying pyranometer mounting equipment

Pyranometer Brackets

Requirements:

- Brackets should be made as low-profile as possible.
- Bracket material and cross section is not important as long as it is sturdy and weather resistant.
- Pyranometers should be mounted horizontally level and on the same plane as the PV array (respectively).
- Any conductive parts should be grounded to main array frame.

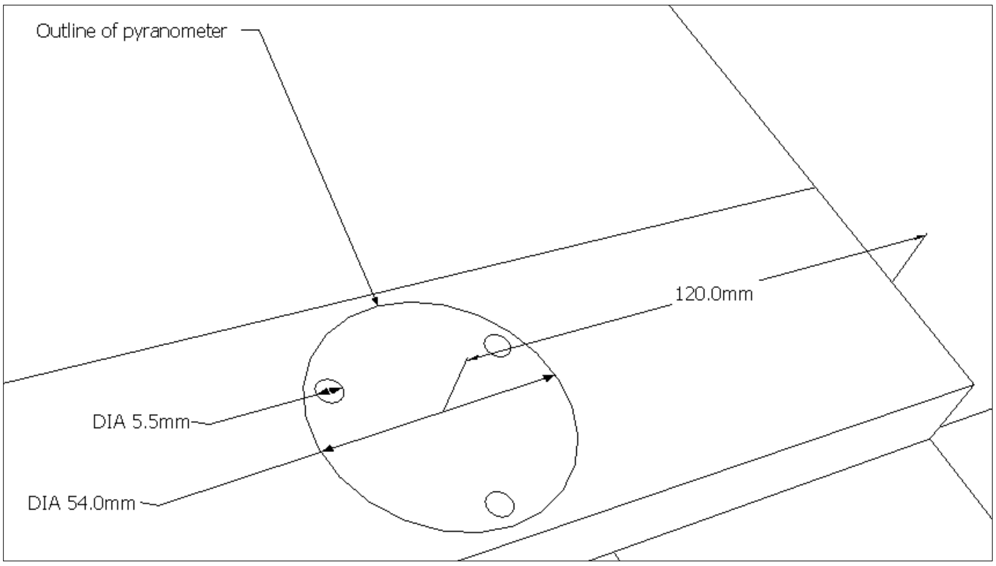

Figure 19 - Pyranometer mounting bracket [view 1]

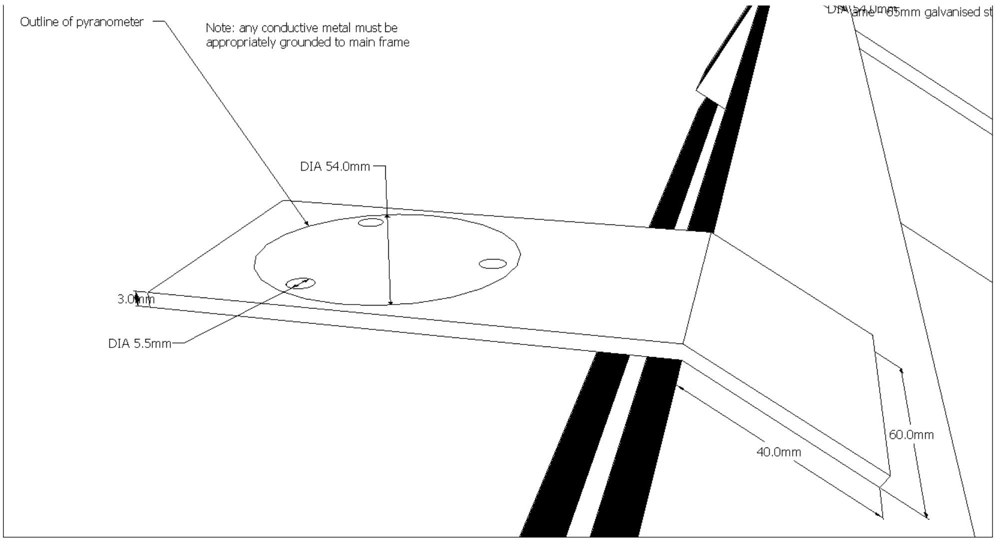

Figure 20 - Pyranometer mounting bracket [view 2]

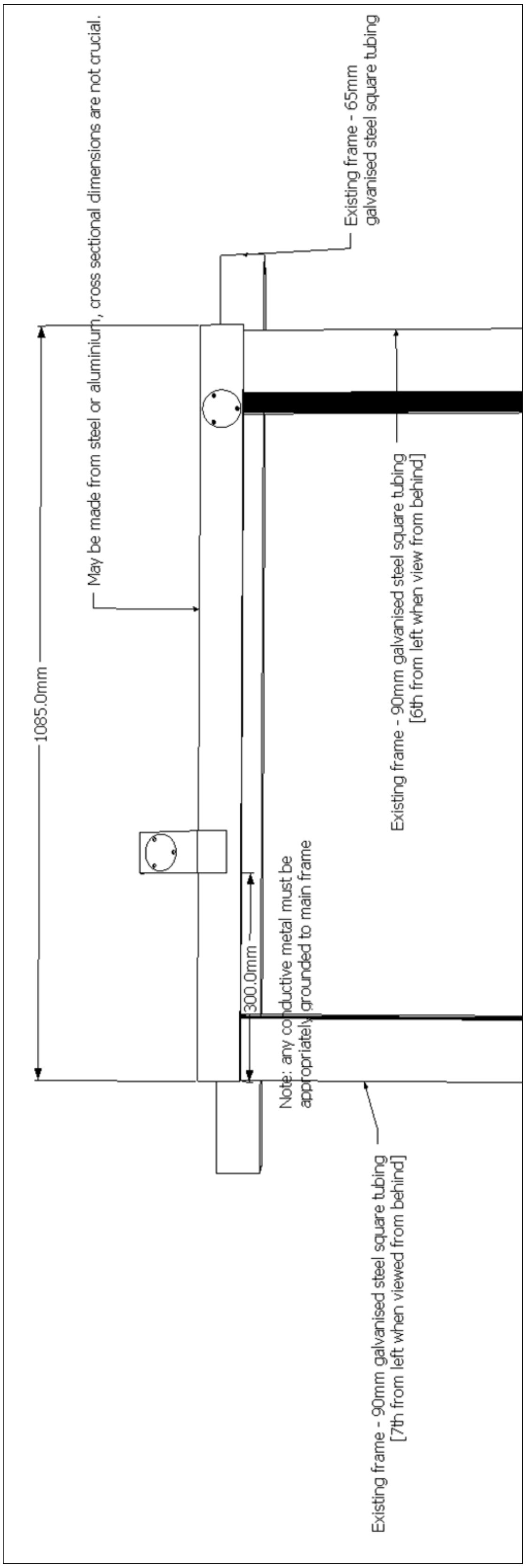

Figure 21 - Pyranometer mounting bracket [view 3]

Wind Measurement Sensors

Requirements:

- Anemometers should be installed approximately 700mm above the PV array and 1200mm to the East and West.
- Wind direction sensor should be installed with West anemometer.
- Any conductive parts should be earthed.
- See figure below for sensor positioning in relation to array.

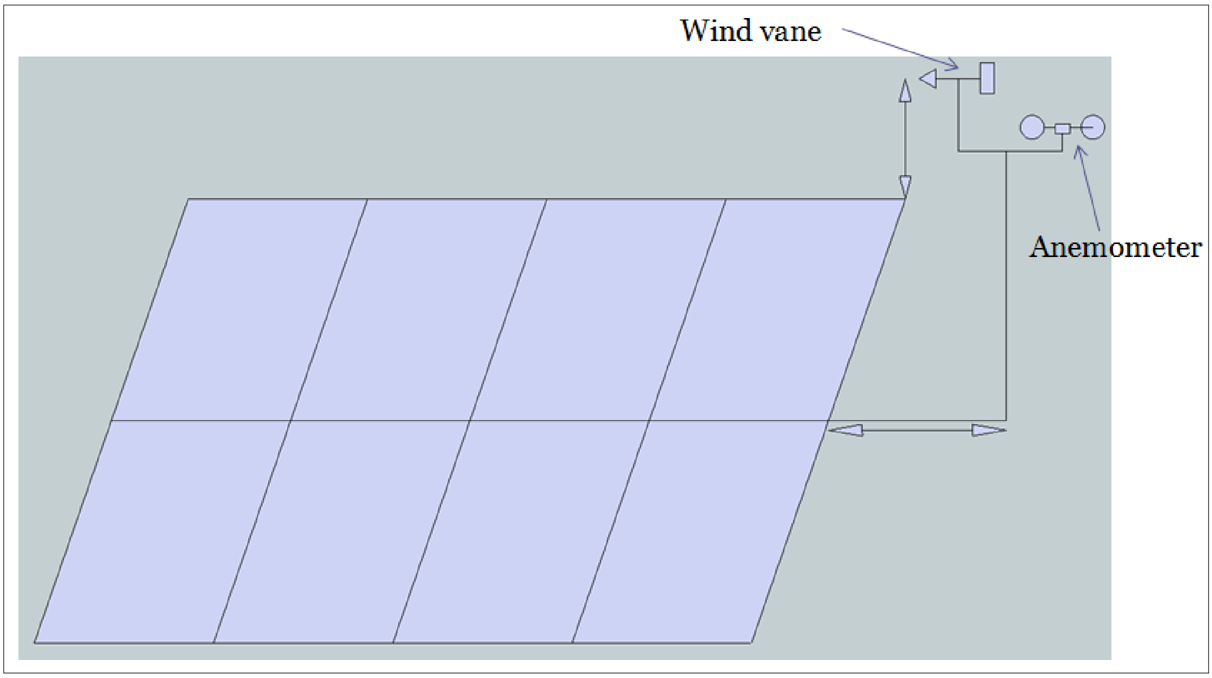

Figure 22 - Wind sensor mounting bracket